Fermi National Accelerator Laboratory

PPD / Mechanical Support / Engineering Analysis

Transient Thermal, Structural, Buckling and Modal Analyses for Mu2e Hayman2 Target Under Beam Cycle

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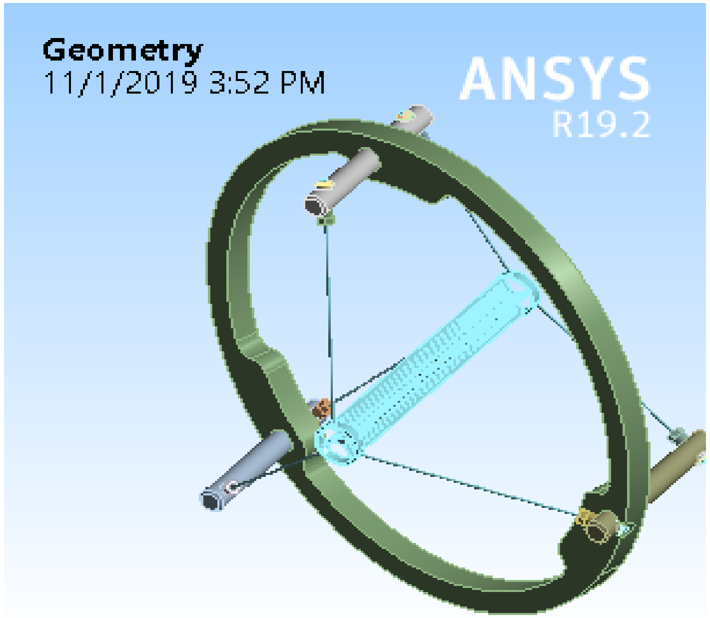
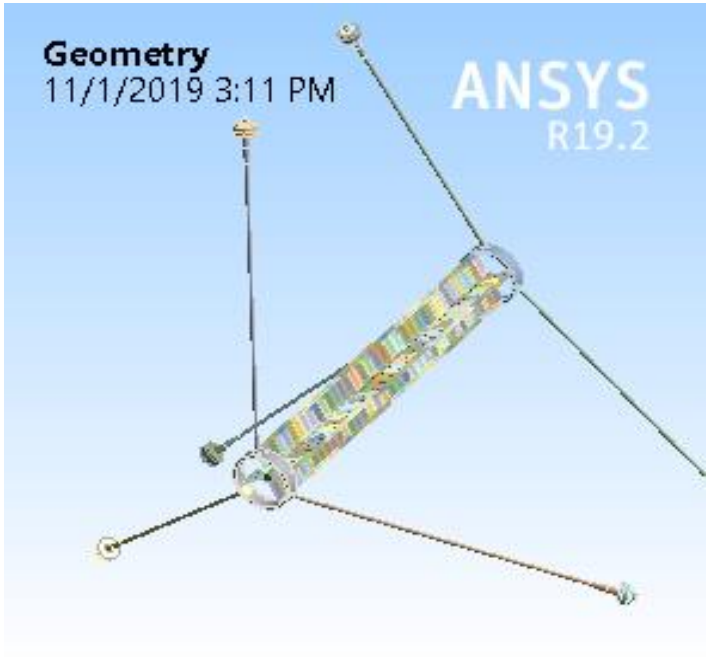
Descriptions

- **Mu2e Hayman2 Target is subjected to the beam cycle. The duration of a cycle is 1,400 msec. It consists of 380 msec on and 1020 msec off.**
- **The energy deposition was provided by Kevin Lynch DocDB-XXX. The total power is 630.352 W.**
- **Target consists of core and 4 fins with cutouts, two rings and bicycle ring, spokes and spoke supports. The core, the fins and the rings are loaded with energy.**
- **The variable emissivity as a function of temperature is used according to the polynomial equation given by RAL in Mu2e – doc-4305.**
- **Target were inspected at the highest and lowest cyclic temperatures calculated for the steady-state condition.**
- **Spoke and Target were checked against the critical buckling loads under Linear Eigenvalue Buckling and Nonlinear Buckling conditions.**
- **The Target were also tested for it's modal shapes under Pre-stressed and Non-Pre-stressed conditions.**

Target with
Bicycle Ring and Posts



Target without
Bicycle Ring and Posts

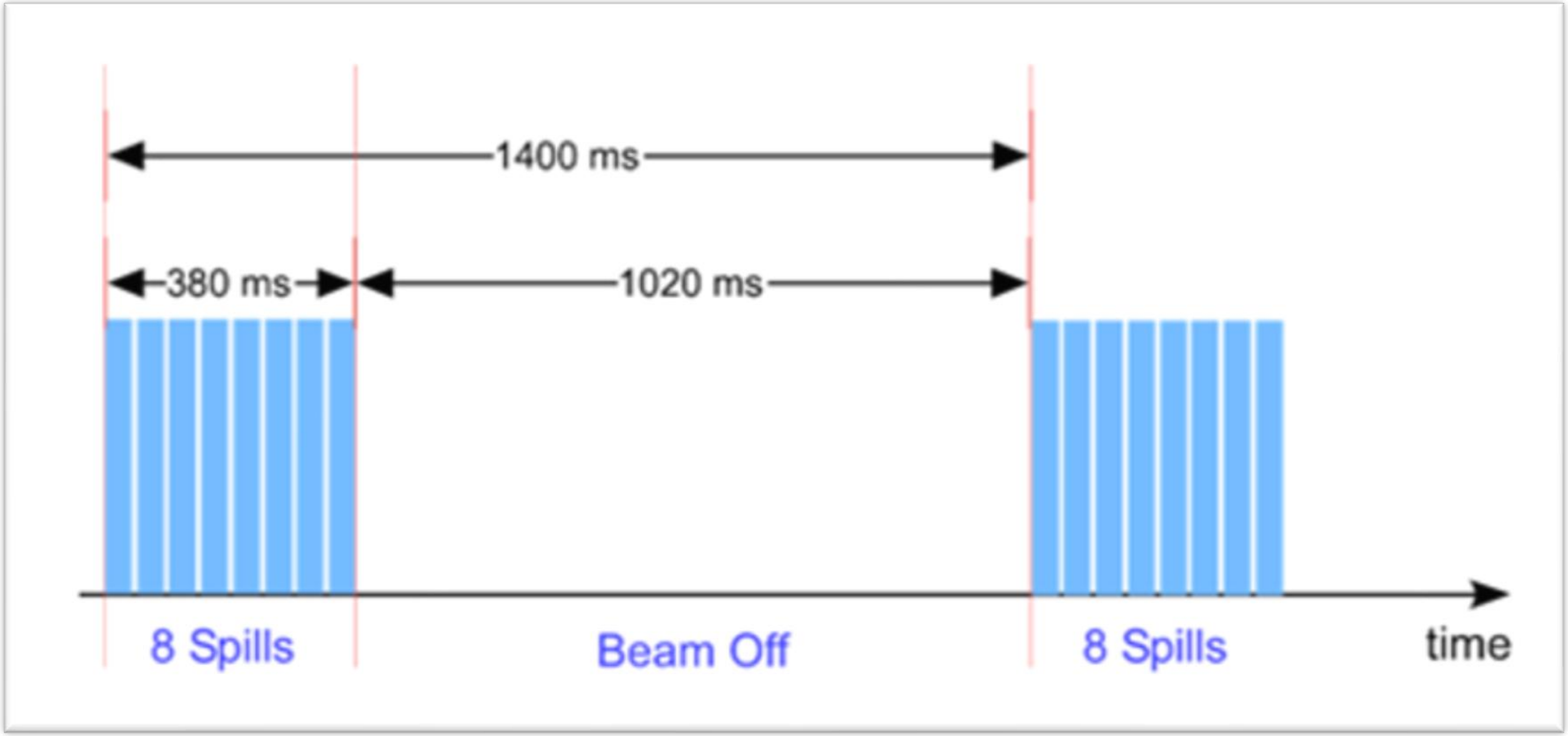


Calculated Component Weight

	Weight (kg)
Core/Fin/Ring/Spoke (Tungsten)	0.424
Keeper/Split Nut (Stainless Steel)	0.029
Bicycle Ring/Post/Bolt(Stainless Steel)	11.554
Total	12.007

Part 1- Target under Beam Cycling

Beam Cycle Duration

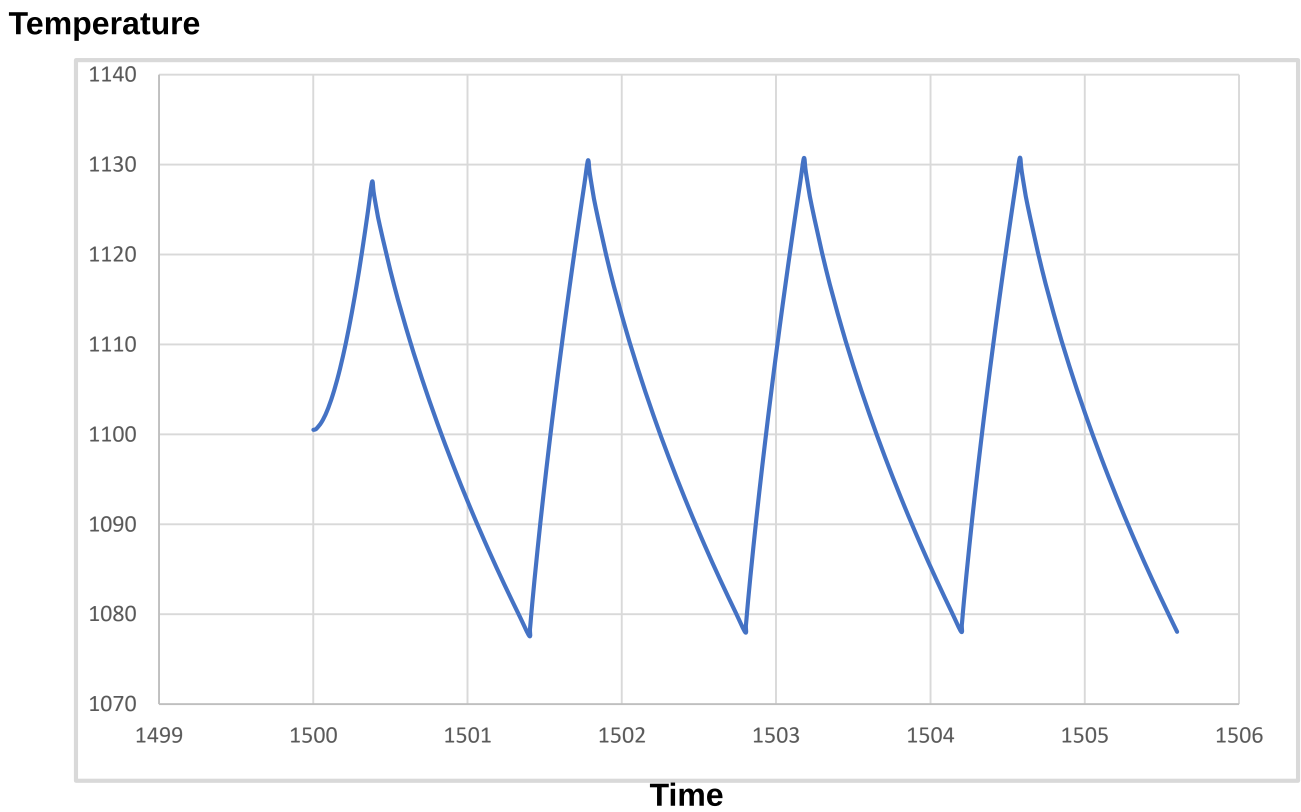


Target Energy Deposition Distribution

	Core	Fin	No of Fin	Rings	Total
Target - Watts	**549.983**	**18.446**	**4**	**6.585**	**630.352**

Part 1- Results

Temperature vs Time in Cycling Load

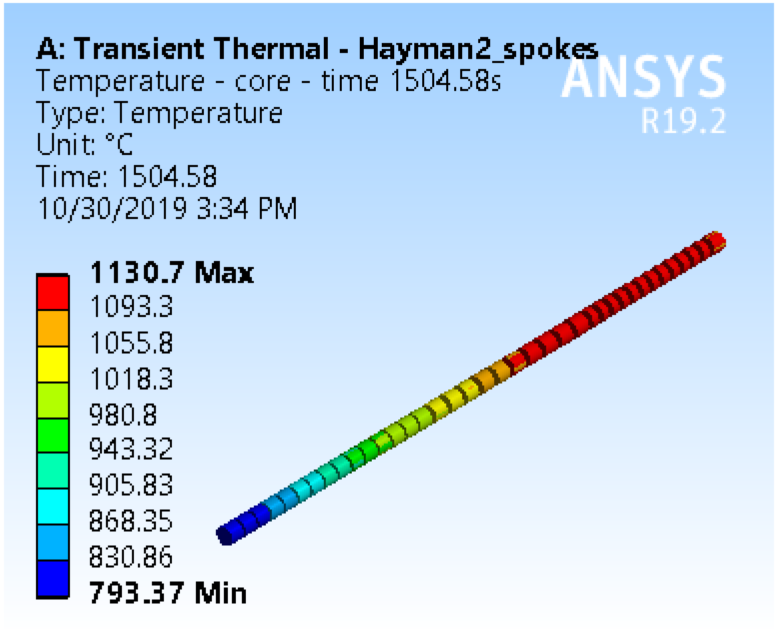


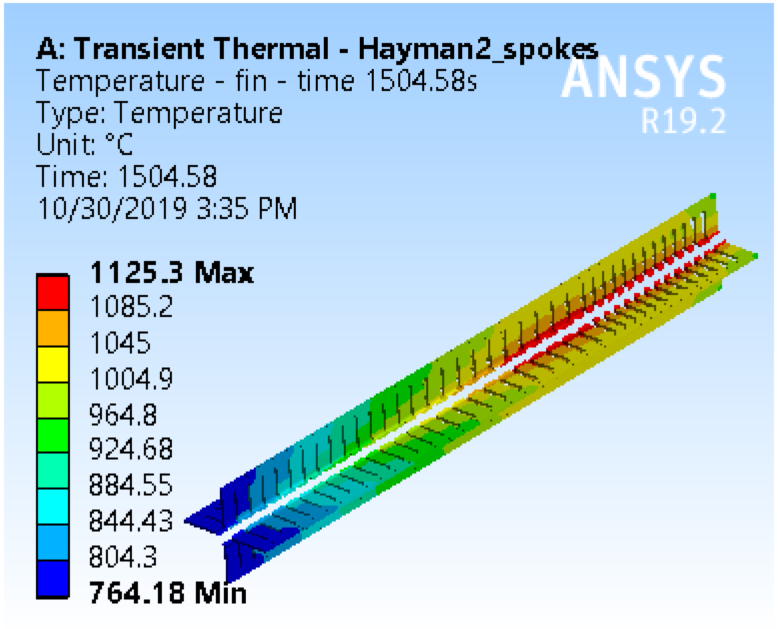
Note that beam cycles were repeated 4 times after the model reached the steady state under the average Edep.

Maximum Temperature in Target

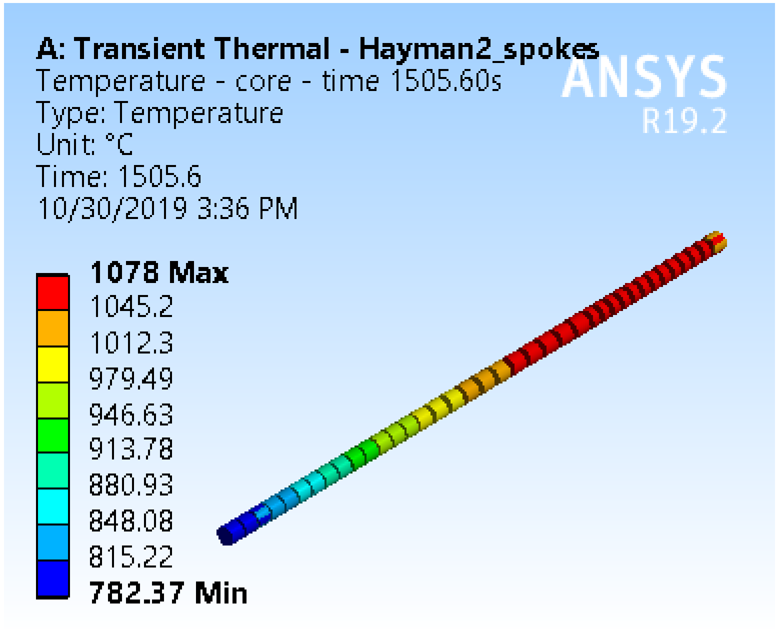
	Beam on	Beam off	Delta T	Average
Core -Temp C	1130.7	1078.0	52.7	1104.35
Fins -Temp C	1125.3	1076.5	48.8	1100.9

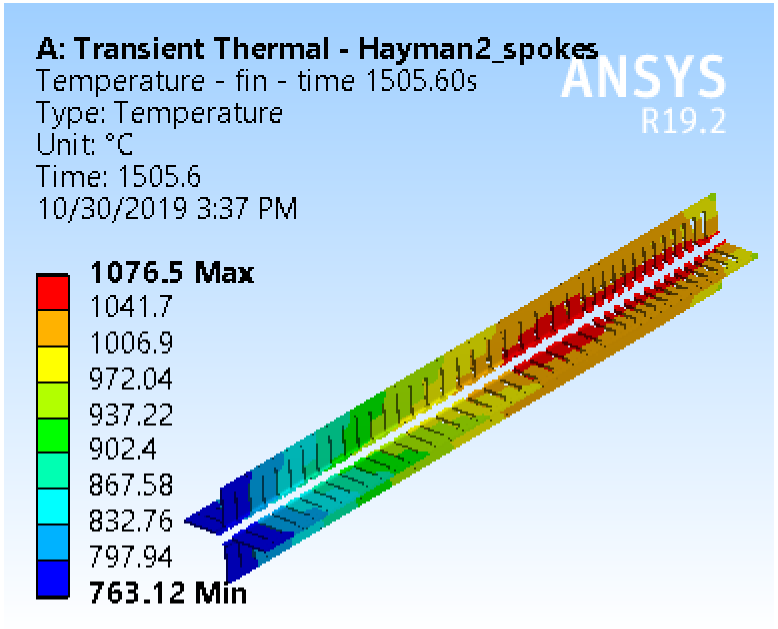
Core and Fin Peak Temperature at 1504.58 sec (Beam on)



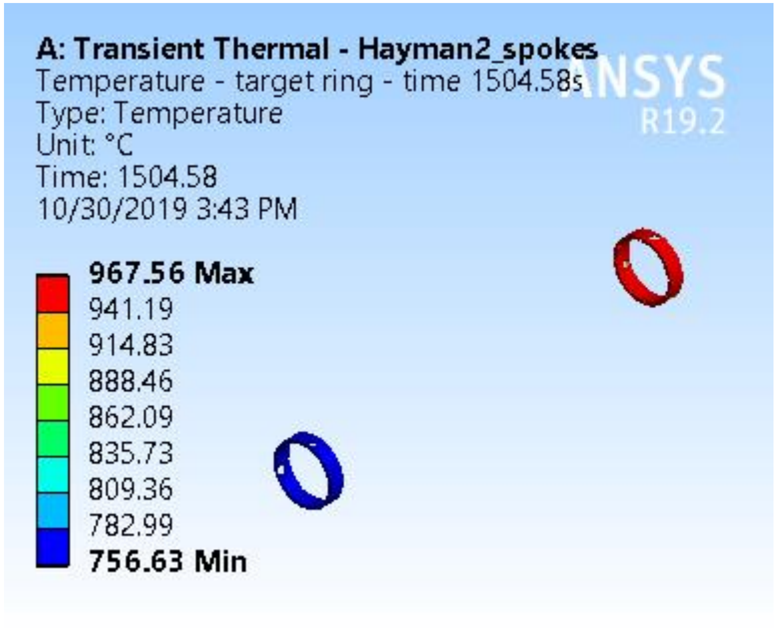


Core and Fins Lowest Temperature at 1505.60 sec (Beam off)

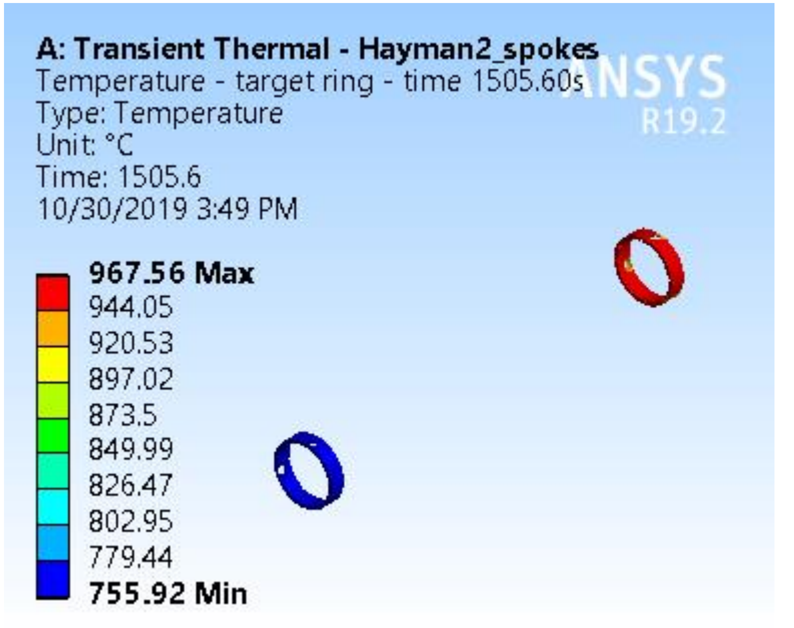




Upstream Ring and Downstream Ring Temperature



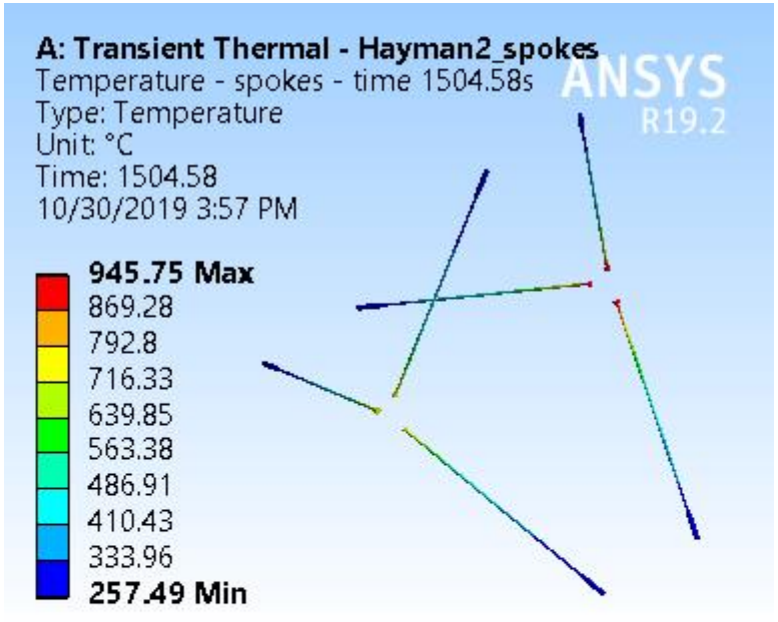
Beam on



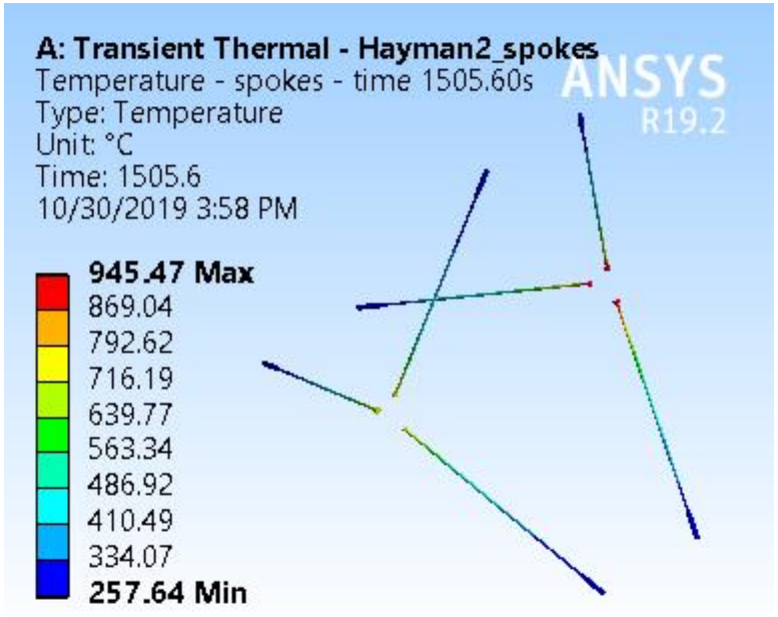
Beam off

There is about 211C difference between the two rings when the beam is on/off

Spokes Temperature



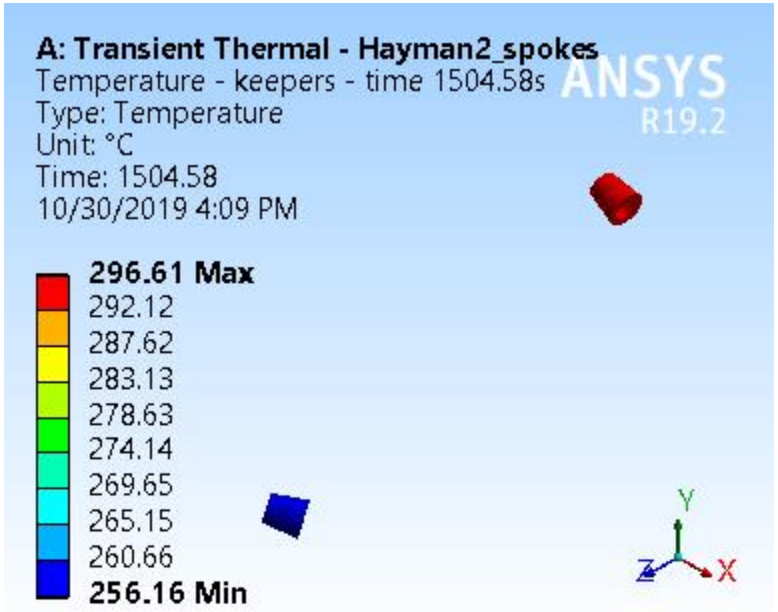
Beam on

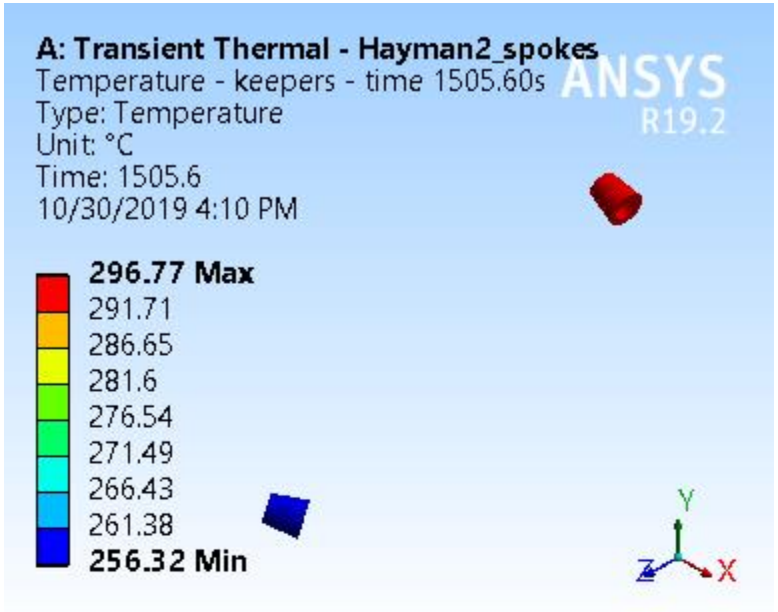


Beam off

There is about 688C difference between the both ends of Spoke when the beam is on/off

Spoke Keepers Temperature



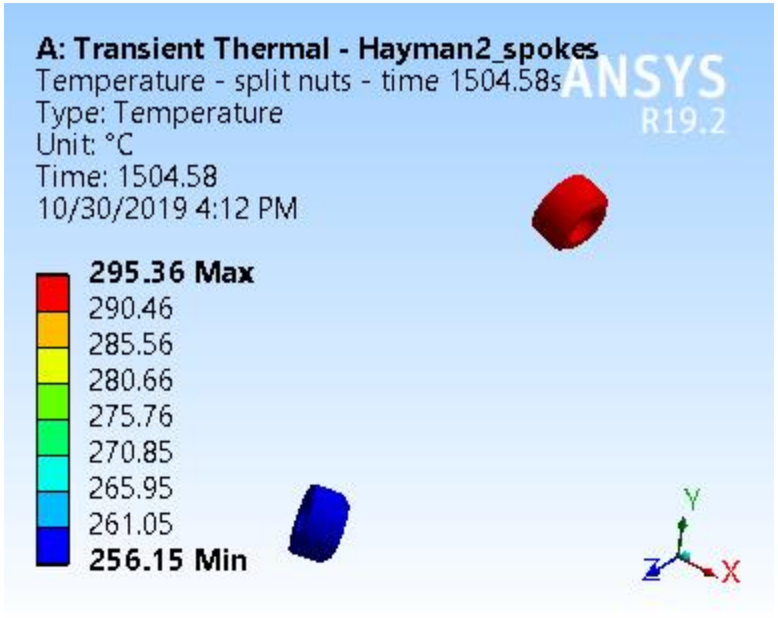


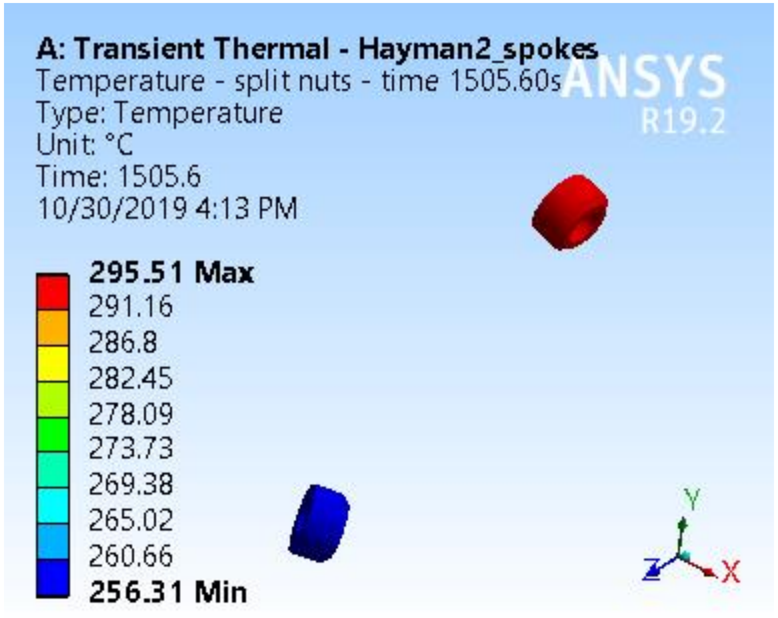
Beam on

Beam off

There is about 40C difference between the hot end and the cold end of the keepers when the beam is on/off

Spoke Split Nuts Temperature





Beam on **Beam off**

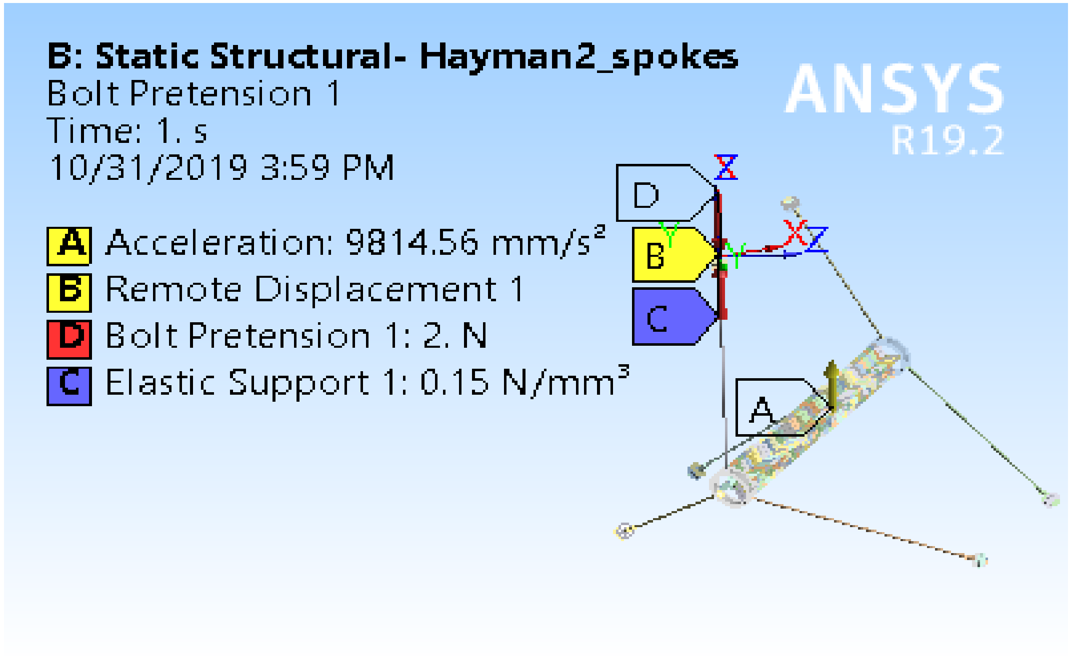
There is about 39C difference between the hot end and the cold end of Split Nuts when the beam is on/off

Part 1- Comments

- **The spherical connections between the Spokes and Target Rings were not applied. The Bonded connections were used for a complete thermal profile transfer onto the Spokes.**
- **This is a conservative approach.**

Part 2- Target Stress and Displacement under Thermal and Structural Loading

Target Boundary Conditions including 2N Preload at Each Spoke



The spring stiffness of 1.876N/mm was applied at the supports

Part 2- Results

Spoke Working Loads under Preload, Beam on and Beam off Conditions

Spoke1	Working load (N)
Preload	2.000
Beam on	1.929
Beam off	1.928

Spoke2	Working load (N)
Preload	1.999
Beam on	1.934
Beam off	1.932

Spoke3	Working load (N)
Preload	1.9999
Beam on	1.9119
Beam off	1.9117

Spoke4	Working load (N)
Preload	2.000
Beam on	1.789
Beam off	1.792

Spoke5	Working load (N)
Preload	1.999
Beam on	1.827
Beam off	1.821

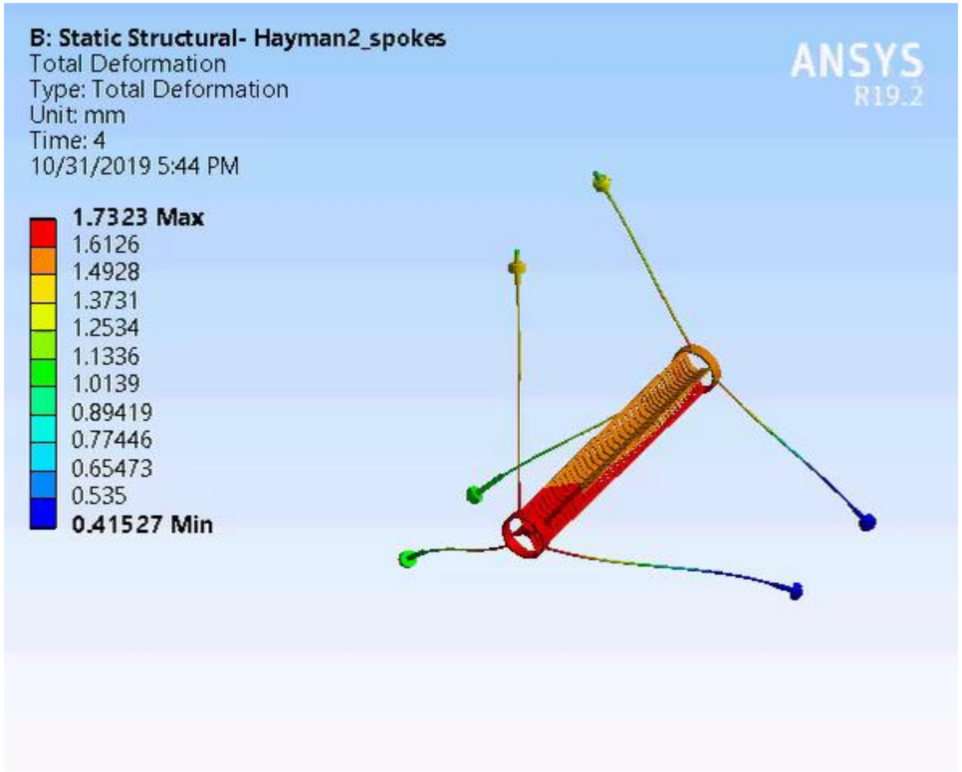
Spoke6	Working load (N)
Preload	1.999
Beam on	1.803
Beam off	1.809

This shows all Spokes were in tension at all times

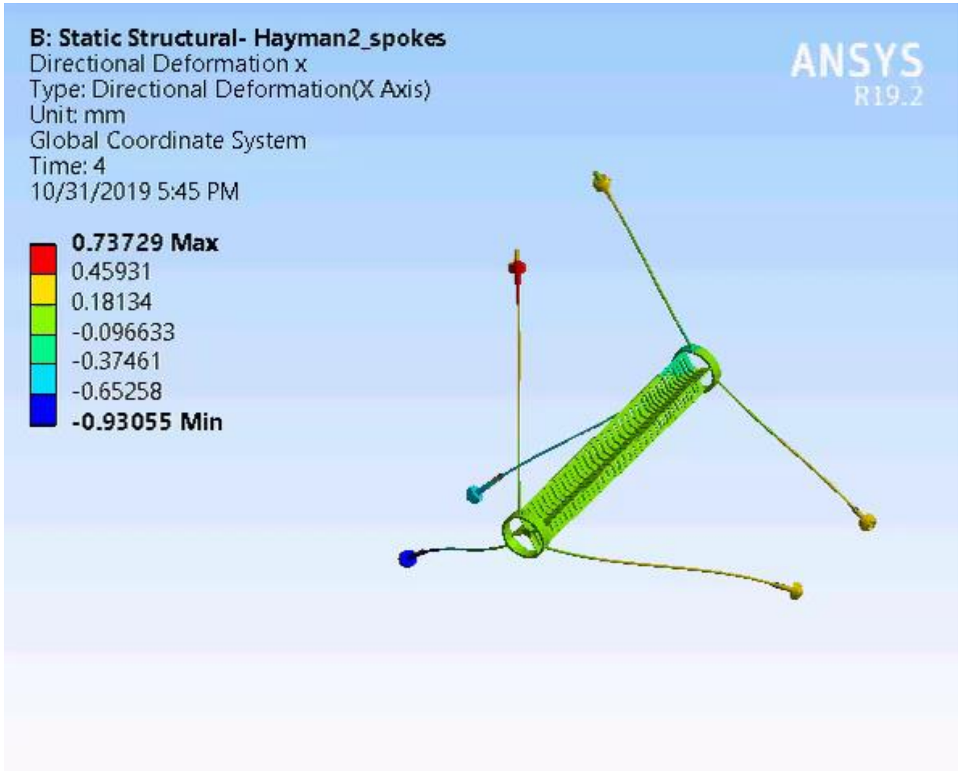
Target Displacement under Preload, Beam on and Beam off Conditions

Total U (mm)	Minimum	Maximum	Average
Preload	0.36	1.64	1.34
Beam on	0.41	1.73	1.36
Beam off	0.42	1.73	1.36
Total Ux (mm)	**Minimum**	**Maximum**	**Average**
Preload	-1.02	0.77	0.00
Beam on	-0.93	0.74	0.00
Beam off	-0.93	0.74	0.00
Total Uy (mm)	**Minimum**	**Maximum**	**Average**
Preload	-1.64	0.70	-1.25
Beam on	-1.69	0.67	-1.25
Beam off	-1.69	0.67	-1.25
Total Uz (mm)	**Minimum**	**Maximum**	**Average**
Preload	-0.54	0.58	0.00
Beam on	-0.52	0.57	0.03
Beam off	-0.52	0.57	0.02

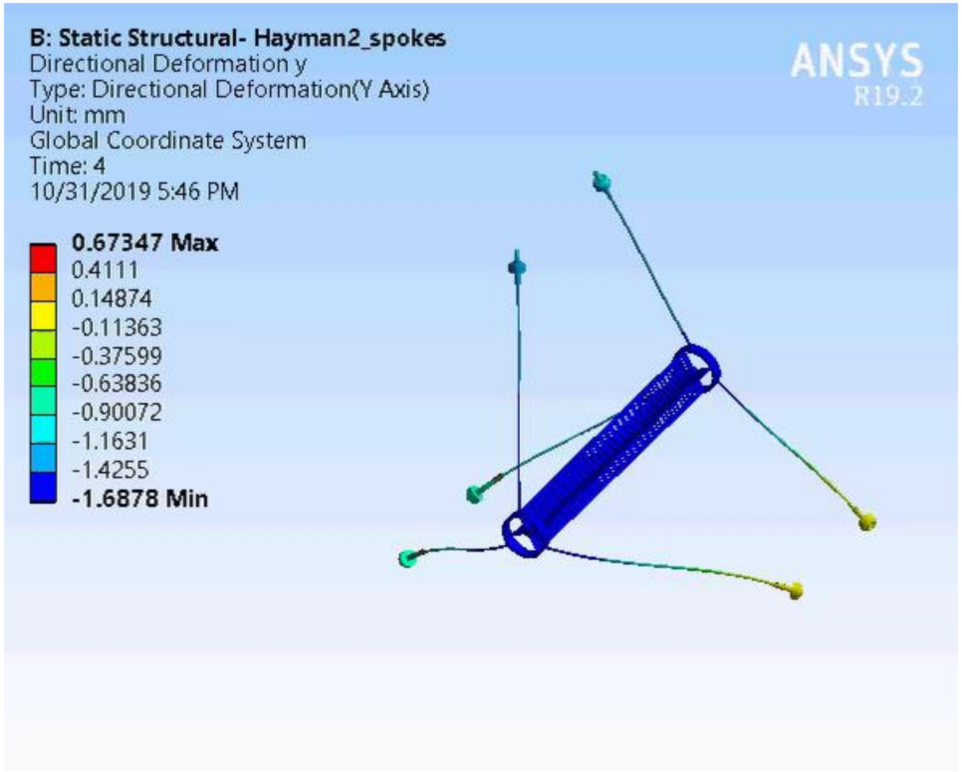
The Animated Total Deformation under Preload, Beam on and Beam off Conditions



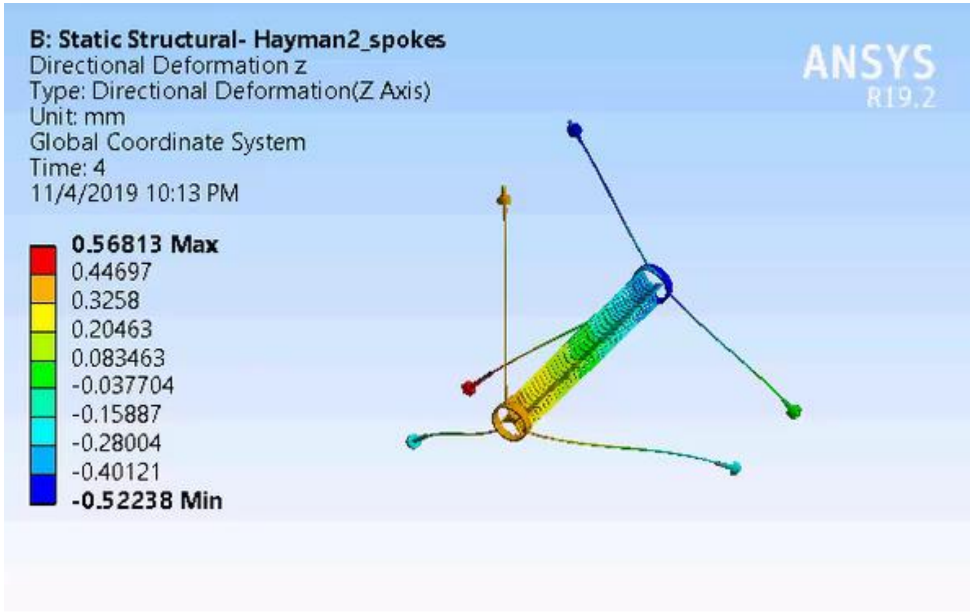
The Animated Directional Deformation X under Preload, Beam on and Beam off Conditions



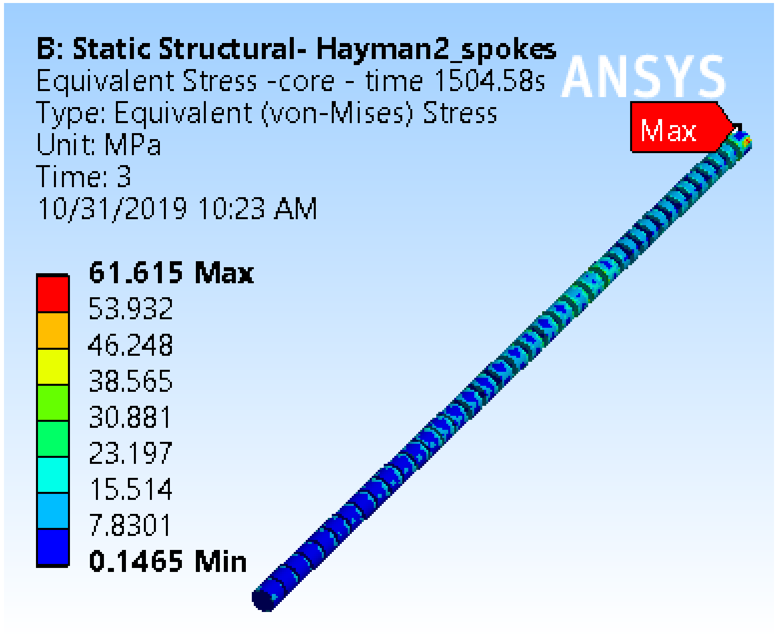
The Animated Directional Deformation Y under Preload, Beam on and Beam off Conditions

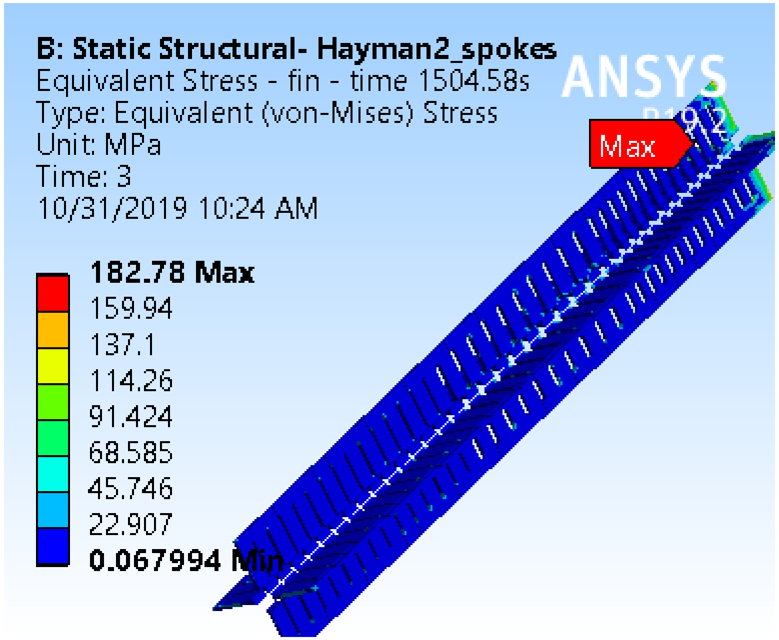


The Animated Directional Deformation Z under Preload, Beam on and Beam off Conditions



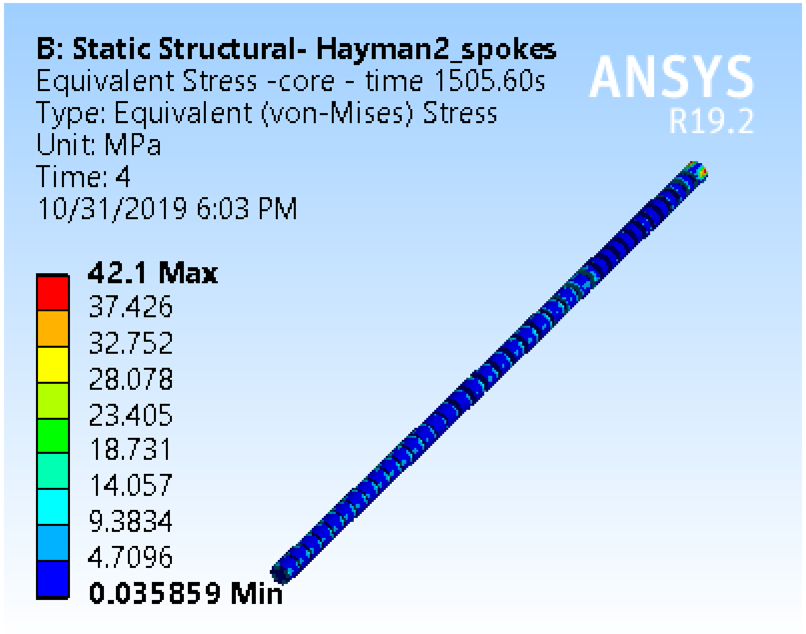
Core and Fins Stress under Peak Temperature at 1504.58s (Beam on)

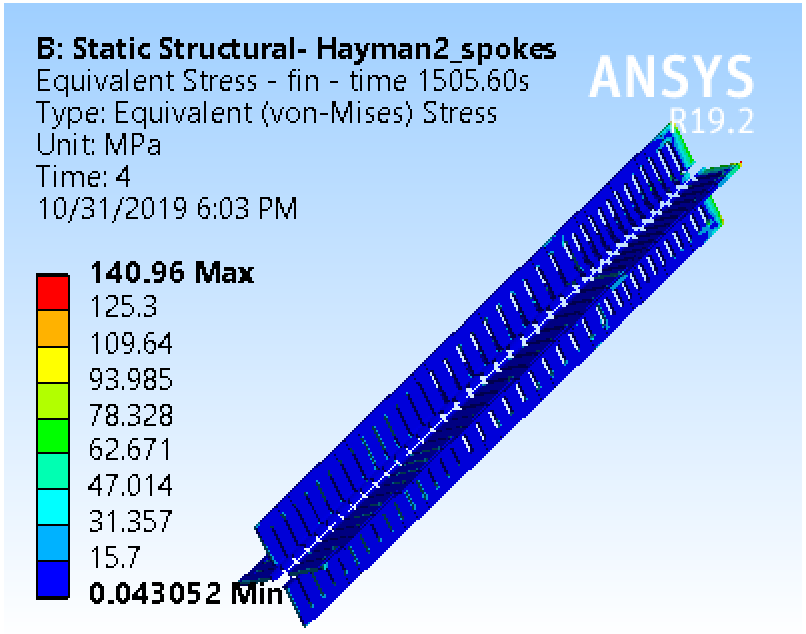




Away from the concentration regions, the stress is much less

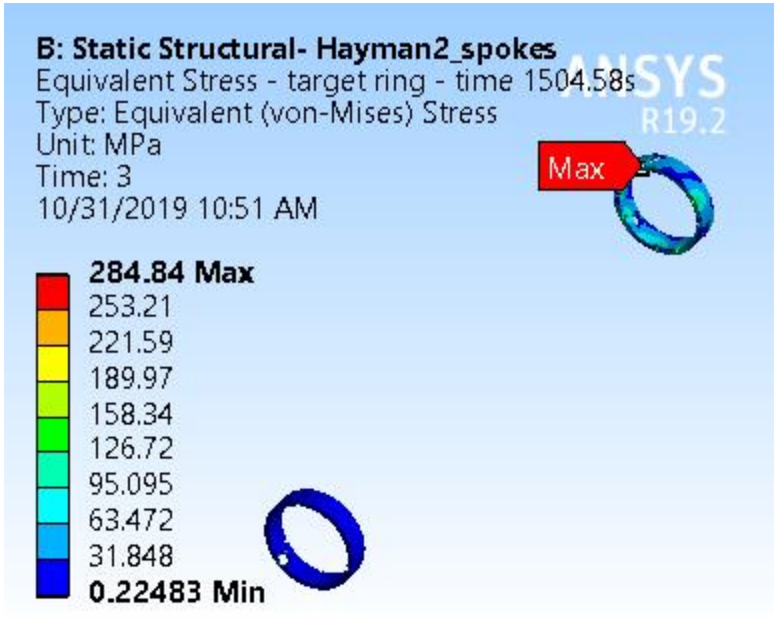
Core and Fins Stress under Peak Temperature at 1505.60s (Beam off)



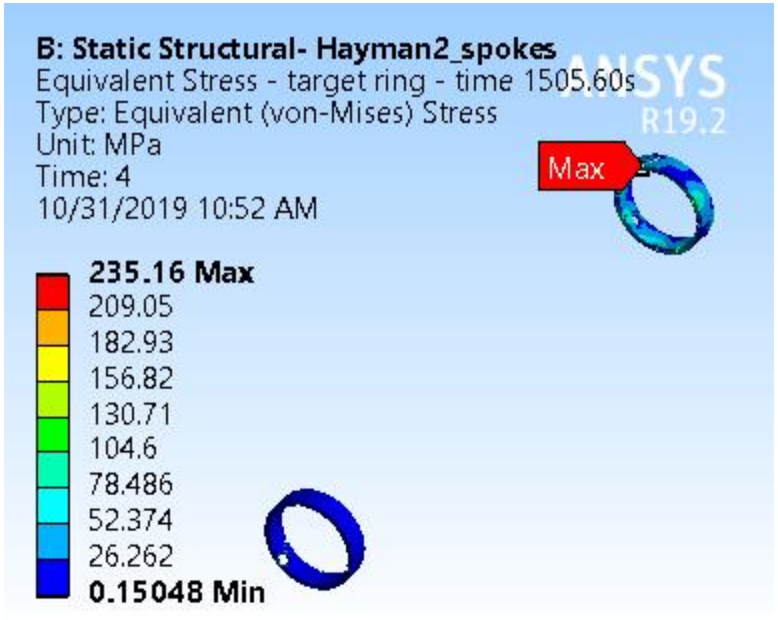


Away from the concentration regions, the stress is much less.

Upstream Ring and Downstream Ring Stress



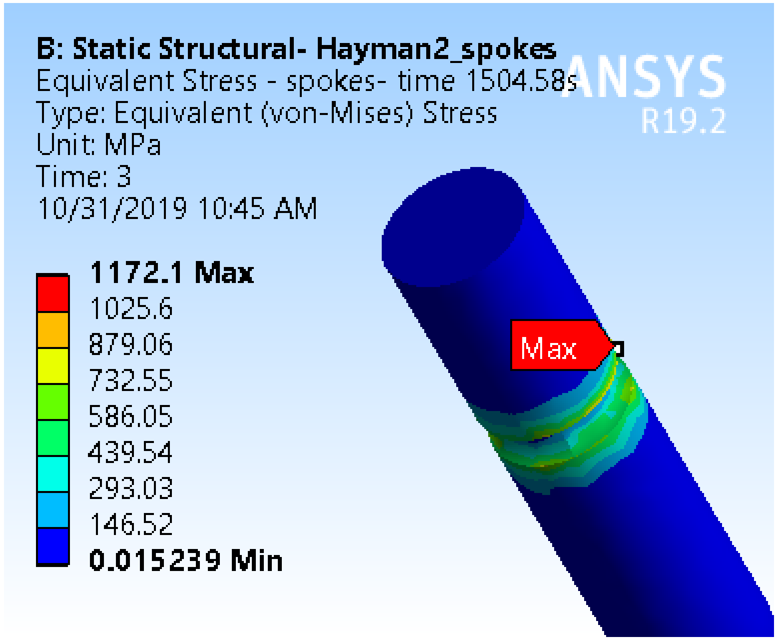
Beam on

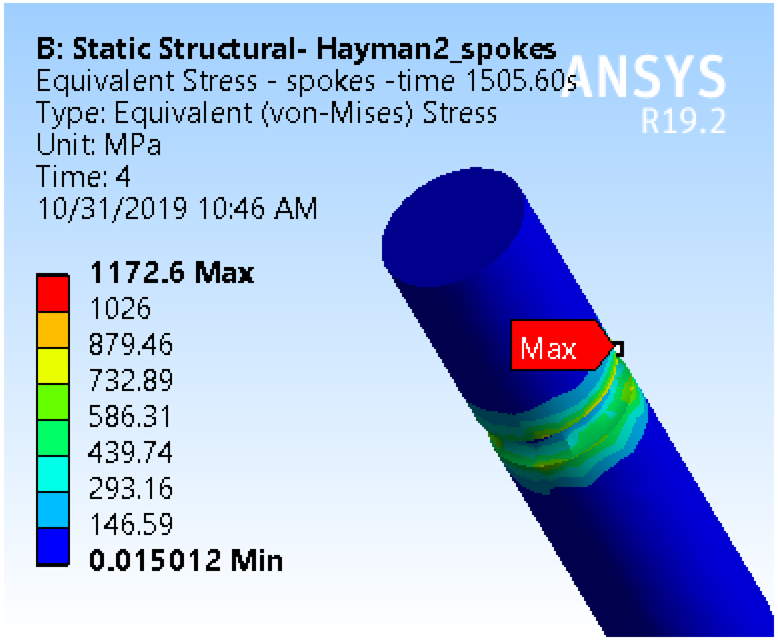


Beam off

There is only slight change in the Ring stress when the beam is on/off.

Spoke Stress

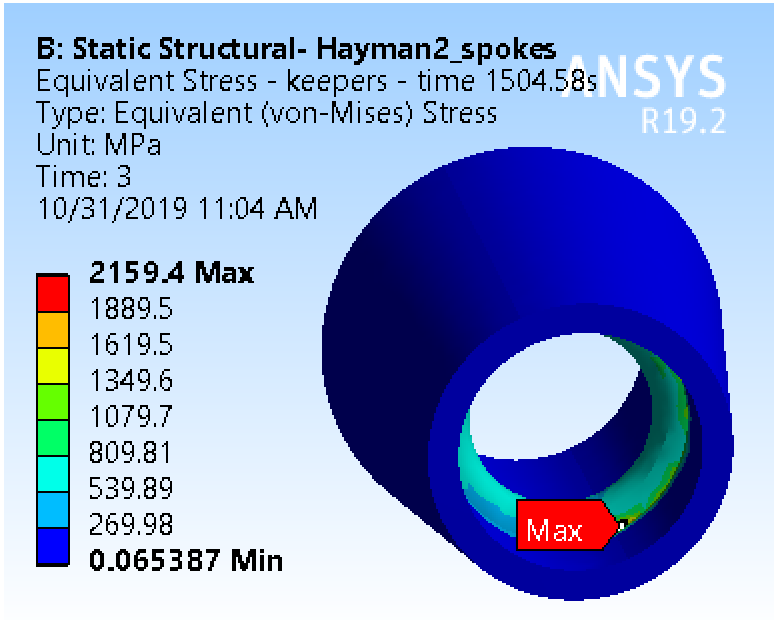




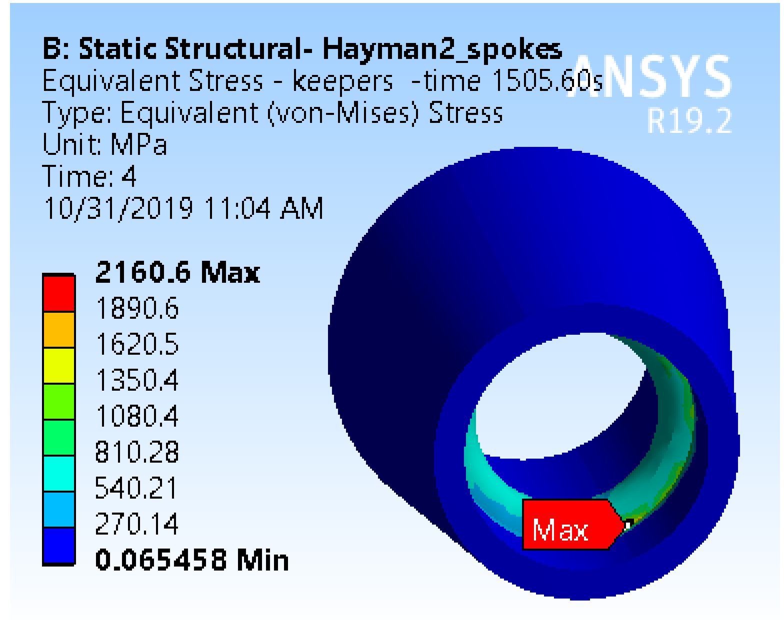
Beam on **Beam off**

Away from the concentration regions, the Spoke stress is much less. There is only slight change in stress when the beam is on/off.

Spoke Keeper Stress



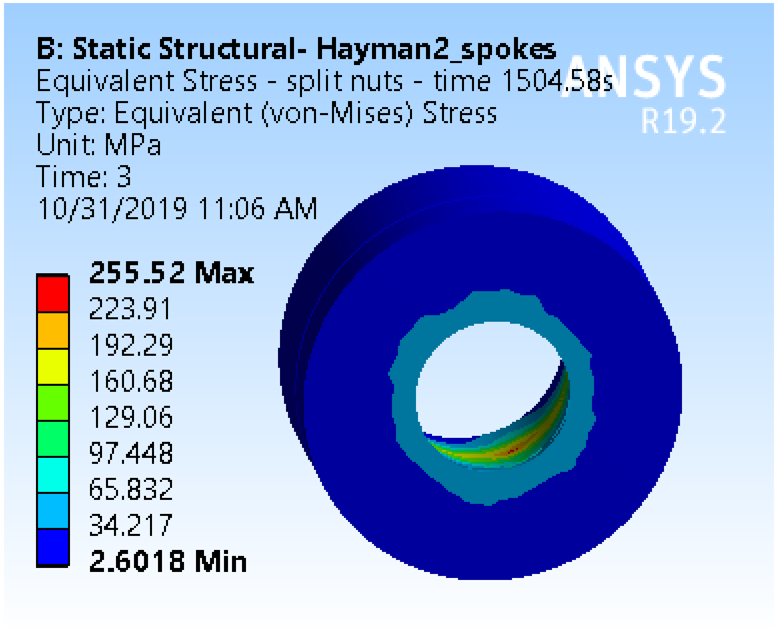
Beam on



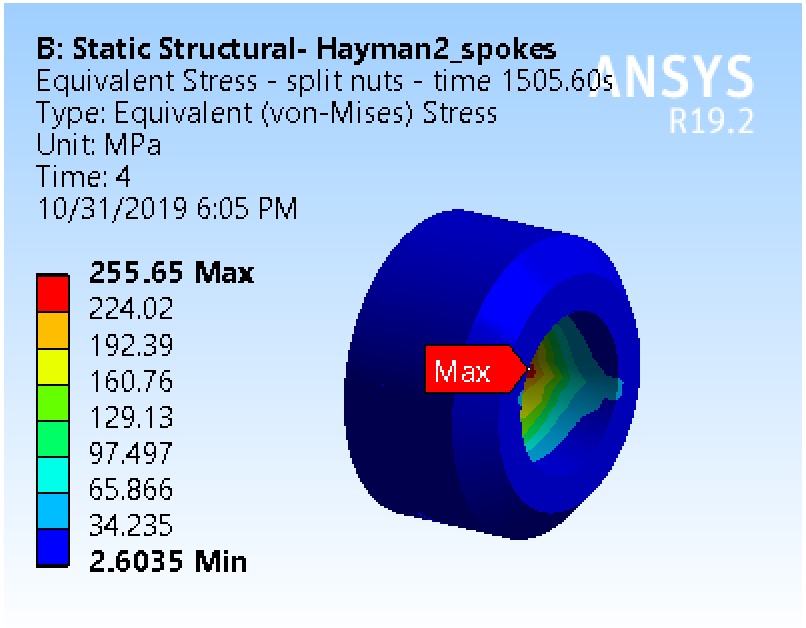
Beam off

Away from the concentration regions, the Spoke Keeper stress is much less. There is only slight change in stress when the beam is on/off.

Spoke Split Nut Stress



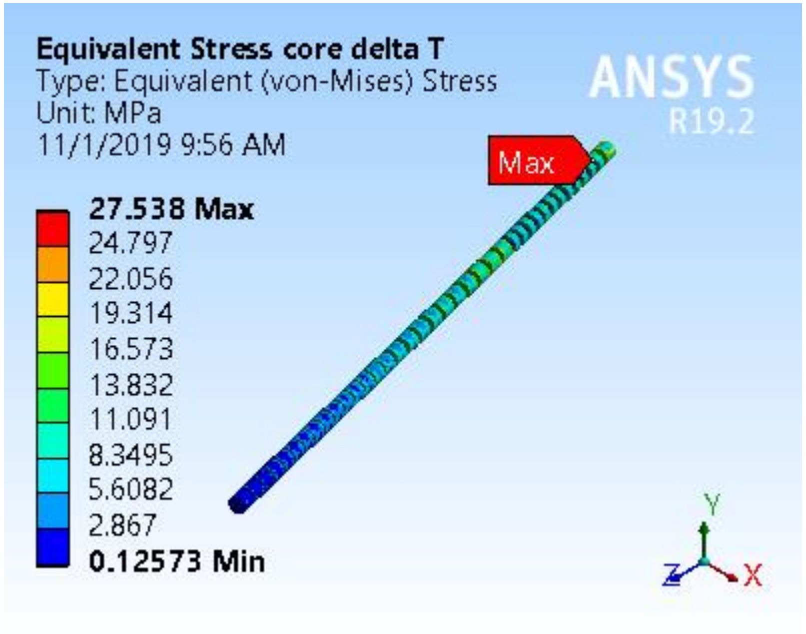
Beam on

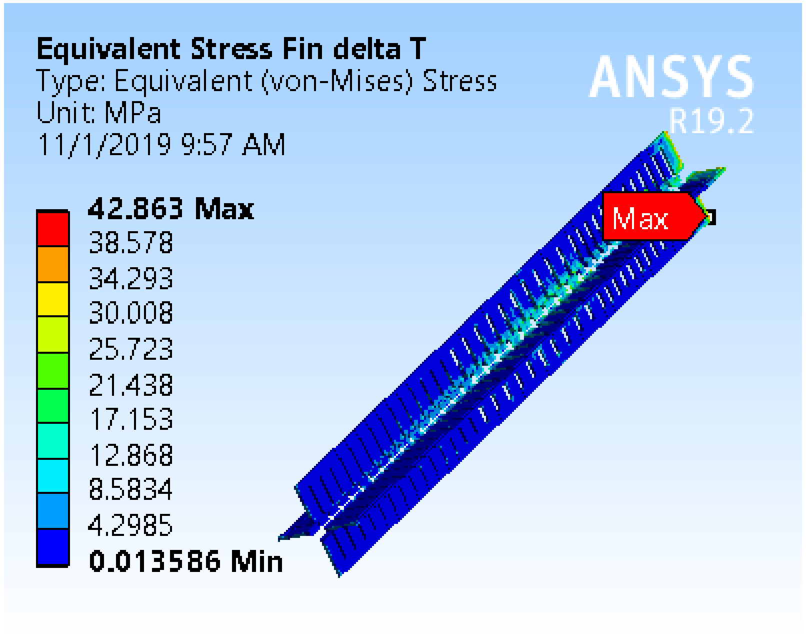


Beam off

Away from the concentration regions, the Split Nut stress is much less. There is only slight change in stress when the beam is on/off.

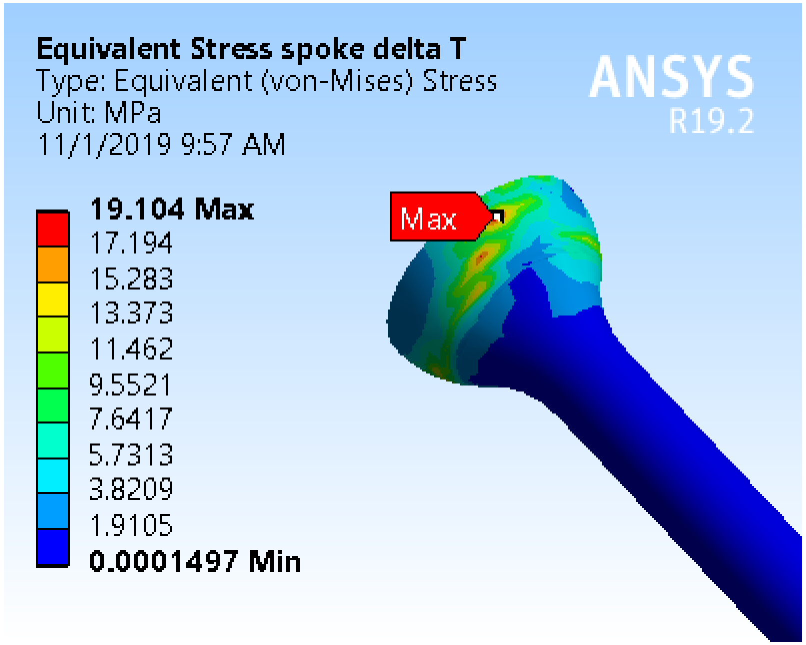
Core and Fin Stress Increment during the Beam Cycling





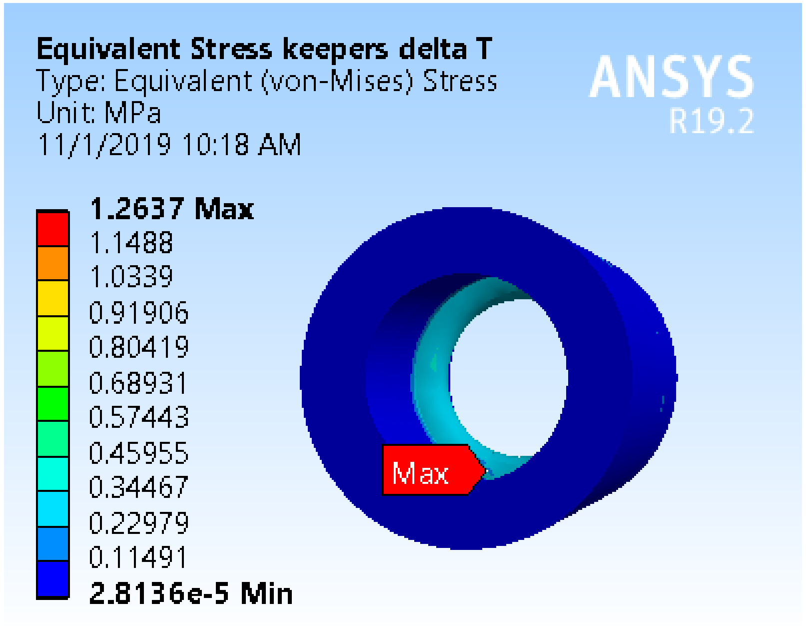
This is a stress excursion and Fatigue may be a concern.

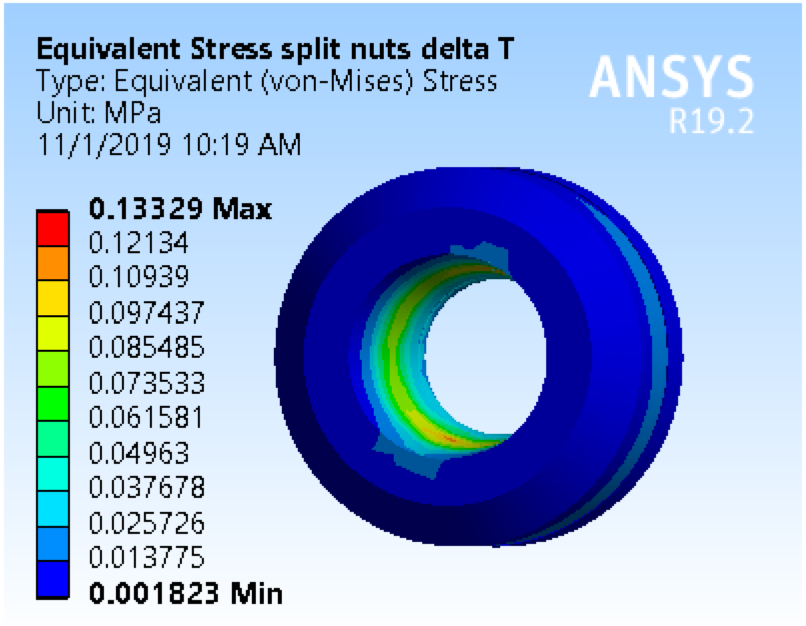
Ring and Spoke Stress Increment during the Beam Cycling



This is a stress excursion and Fatigue may be a concern.

Spoke Keeper and Split Nut Stress Increment during the Beam Cycling





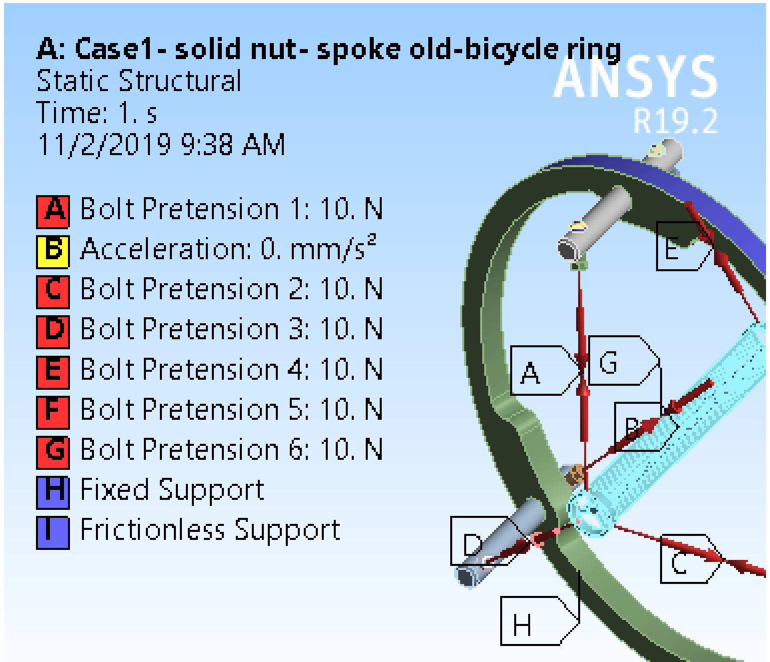
This is a stress excursion and Fatigue may be a concern.

Part 2- Comments

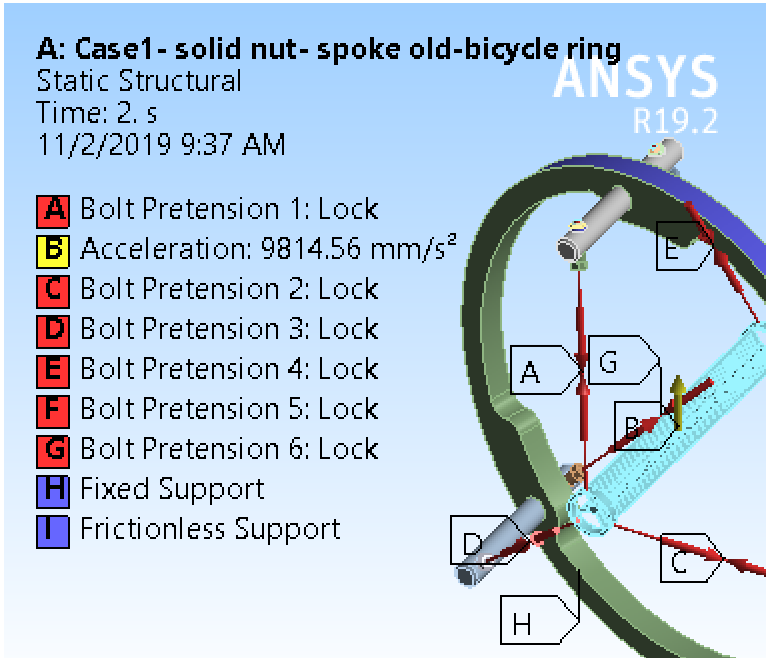
- **Any stress raisers including residual stress and stress concentration should be eliminated by removal of the sharp corners and increasing the radii of the fillets. This will prevent any premature fatigue failure.**
- **The cold work option should be considered to increase the dimensional stability at high temperatures due to the creep deformation.**

Part 3- Target with Bicycle Ring and Posts under Structural Loading only

Target Boundary Condition including 10N Preload at Each Spoke



Step1- Preload

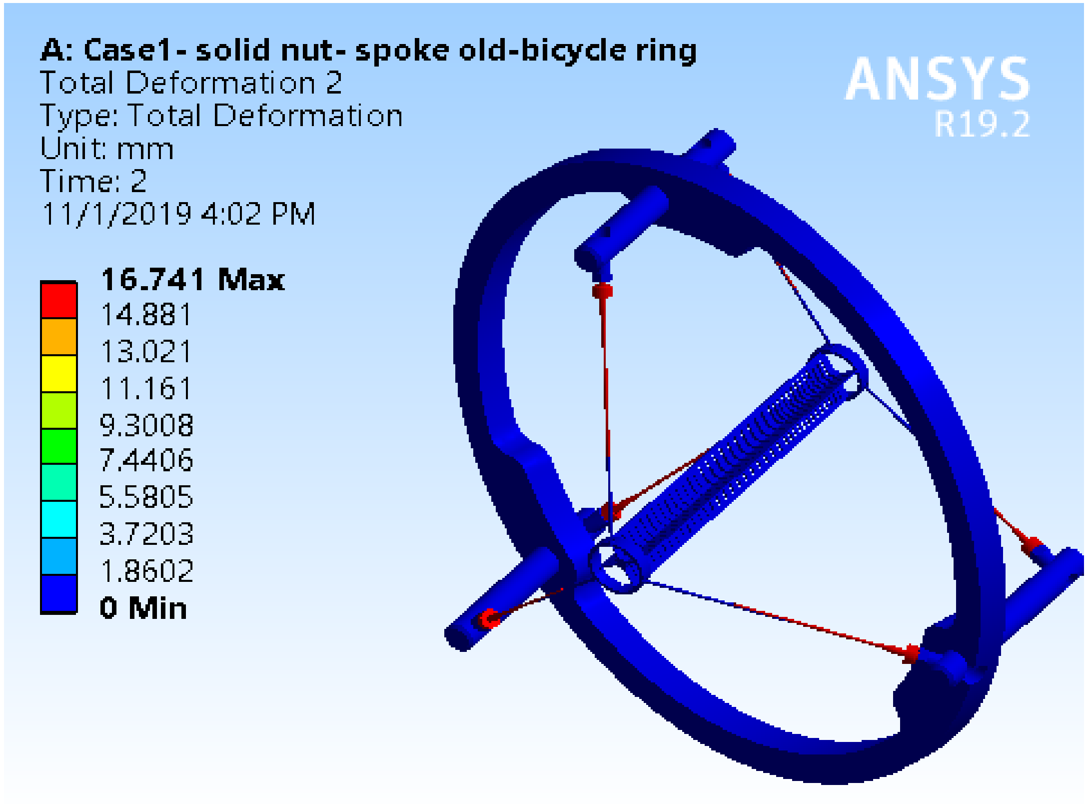


Step2- Preload + gravity

Note the spherical joints were used in the spokes and the target rings

Part 3- Results

Total Displacement in Target



Note Bicycle Ring and Posts deflection is near zero.
Therefore, these component can be ignored intentionally.

Part 3- Comments

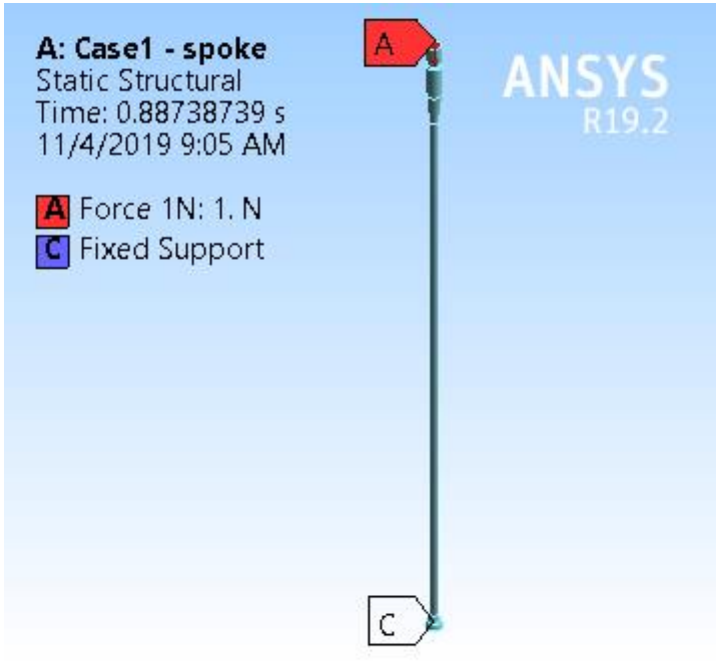
It is completely reasonable to not include Bicycle Ring and Posts in the Part 2 study.

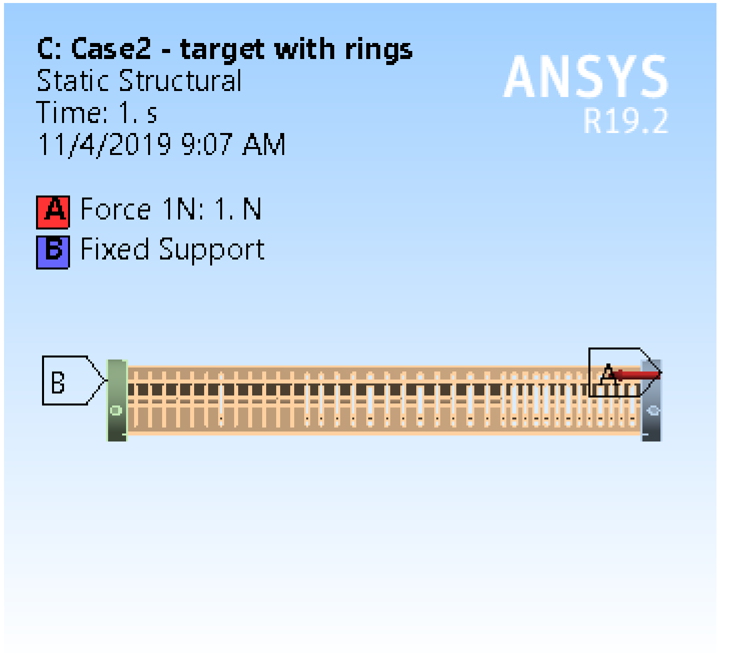
Part 4- Spoke and Target Critical Buckling Load under Linear Eigenvalue Buckling and Non-Linear Buckling Conditions

Linear vs Non-Linear

- **In Linear Eigenvalue Buckling analysis, the goal is to predict the theoretical buckling strength of an ideal linear elastic structure. This method corresponds to the text book approach of Euler Column Solution.**
- **In Non-Linear Buckling analysis, the goal is to find the maximum load at the first limit point when the structure becomes unstable.**
- **Since imperfections and nonlinear behavior prevent most real world structures from achieving their theoretical elastic strength, Non-Linear buckling is more accurate than Linear buckling and is, therefore, recommended for the evaluation of any structures.**

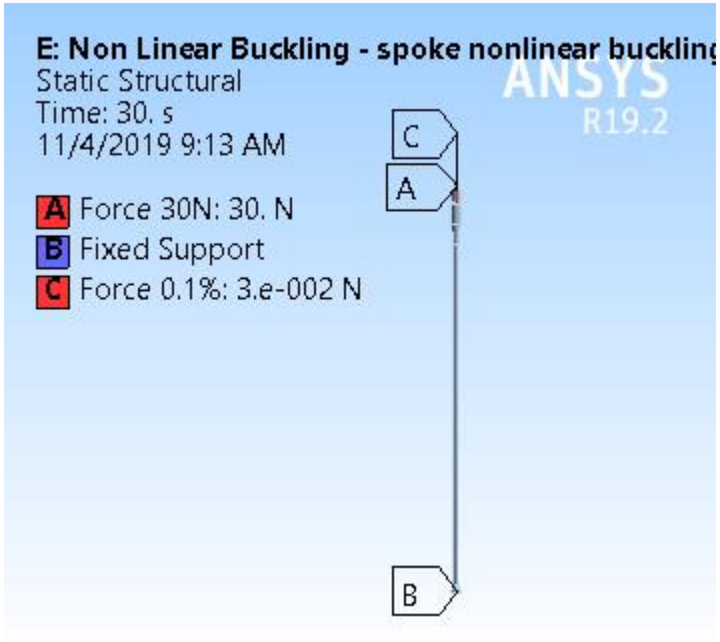
Spoke and Target Boundary Condition under Linear Buckling

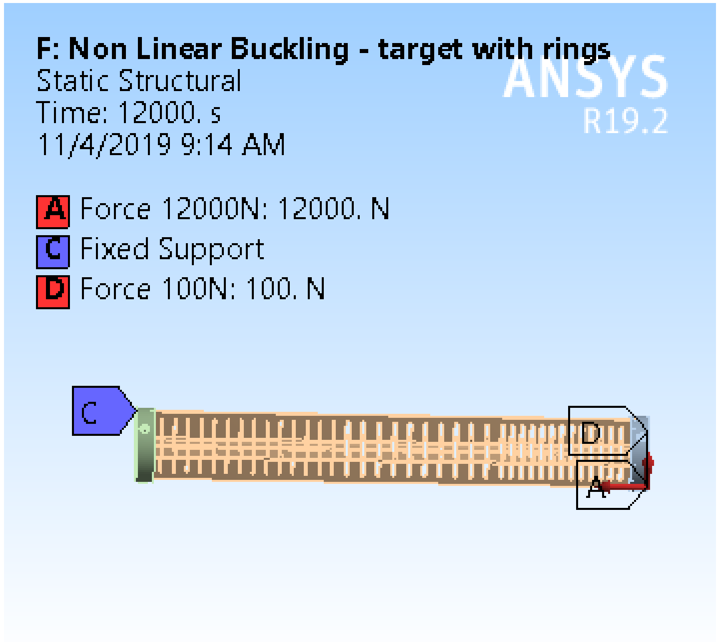




Note the applied load was set to 1N for both cases

Spoke and Target Boundary Condition under Non-Linear Buckling





Note the applied load was set to a value slightly higher than the critical load predicted by the eigenvalue buckling analysis for both cases. Also, a small force was added to initiate buckling.

Part 4- Results

Critical Buckling Load (N) under Linear Buckling

Spoke

Mode	Load Multiplier
1	19.46

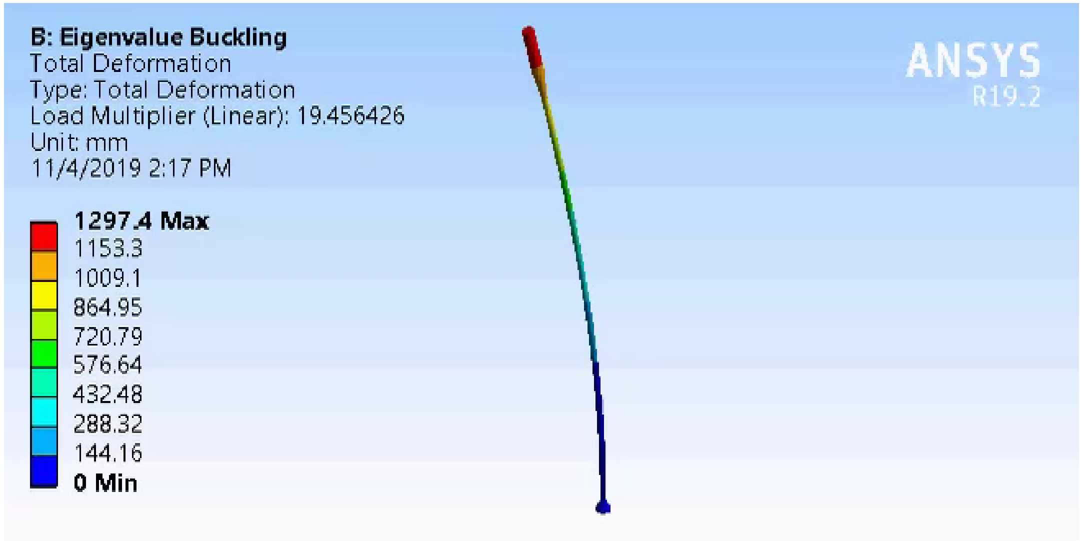
Note the real applied load at Spoke is less than 2N. Therefore, the safety factor is 9.7.

Target

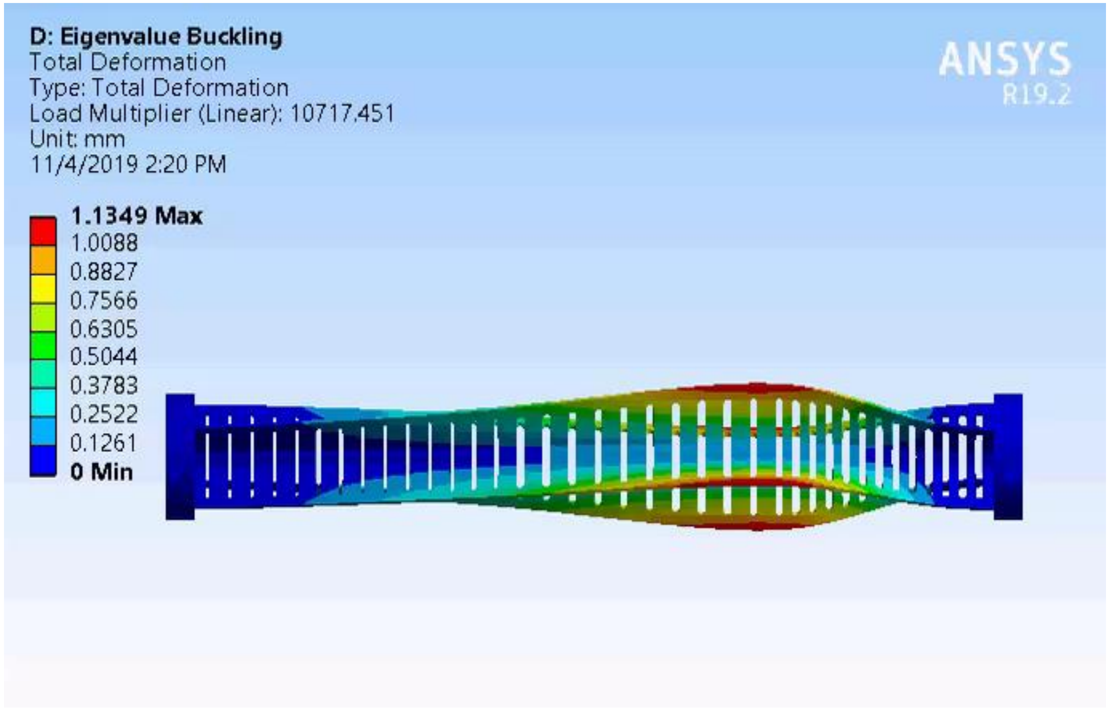
Mode	Load Multiplier
1	10717.45

Since the critical load at Target is enormous, the buckling is not a concern.

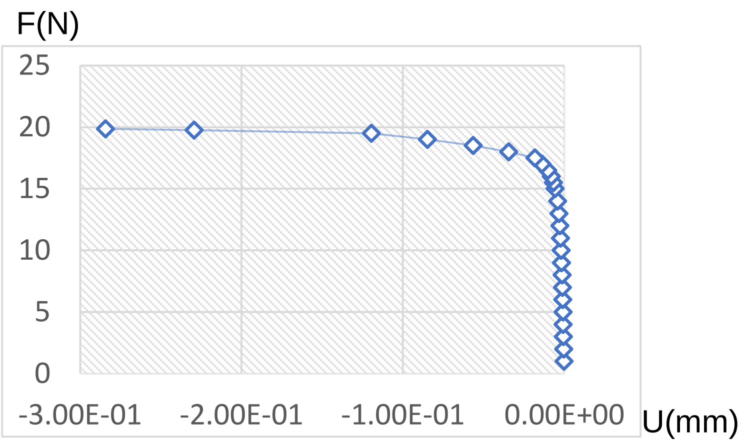
Spoke Mode Shape under Linear Buckling



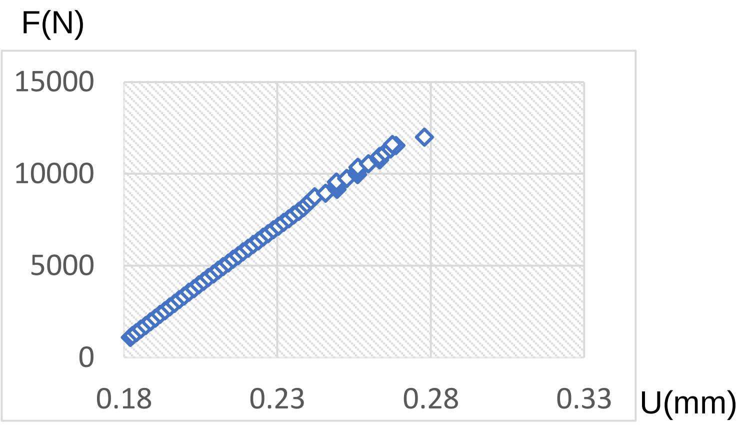
Target Mode Shape under Linear Buckling



Critical Buckling Load (N) at the First Limit Point under Non-Linear Buckling. This is the Maximum Load before the Solution Becomes Unstable.



Spoke Load and Deflection Curve



Target Load and Deflection Curve

A near flat curve indicates buckling. The tangent stiffness will approach zero as the structure nears it's buckling load. Since the critical load for both Spoke and Target remains unchanged, the nonlinear behavior in the structure is not an issue.

Part 4- Comments

- **Spoke is not likely to buckle due to the safety factor.**
- **Target is also not likely to buckle due to the enormous safety margin.**

Part 5- Target Modal Analyses under Pre-stressed and Non Pre-stressed Conditions

Pre-Stressed VS Non Pre-stressed

	Preload	Beam on/off
Pre-stressed	Y	Y
Non Pre-stressed	N	N

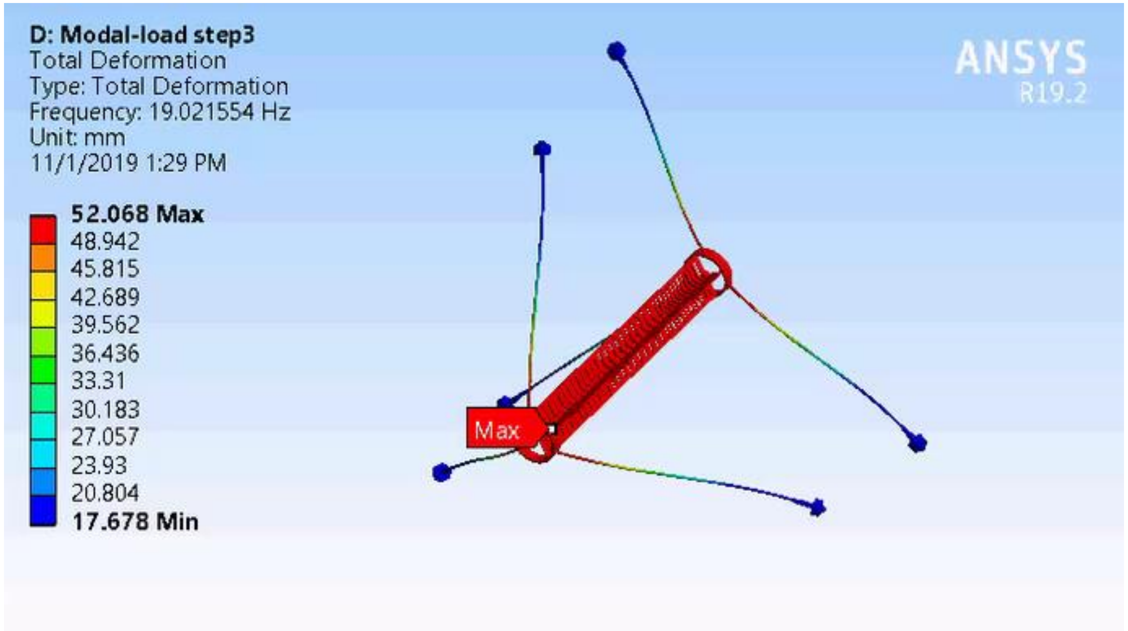
Part 5- Results

Target under Pre-stressed Conditions

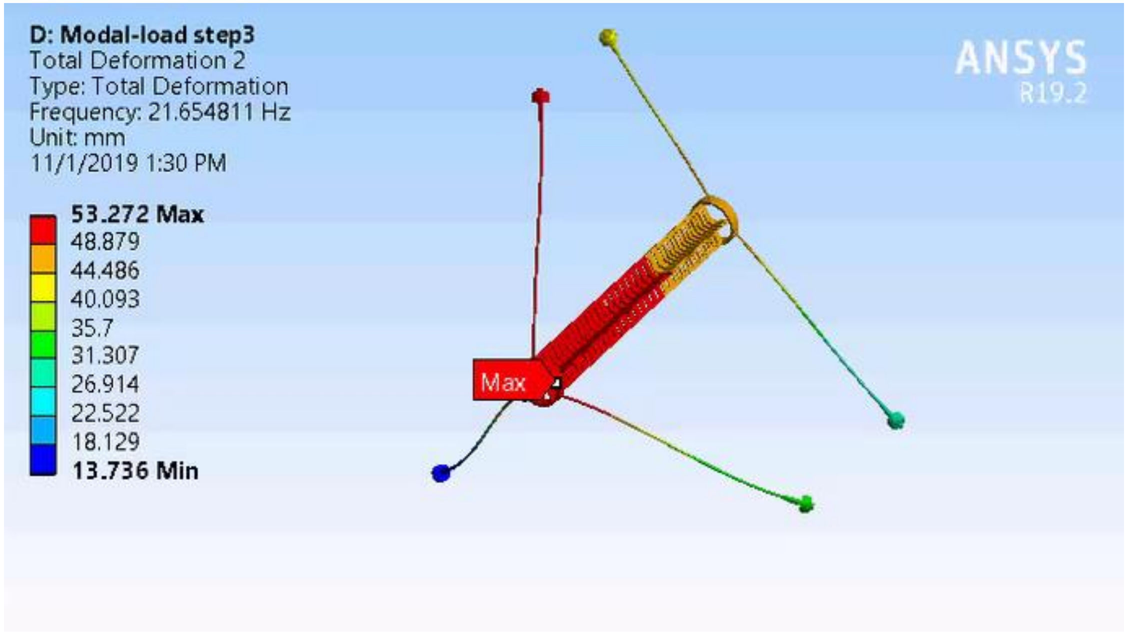
	Preload	Beam On	Beam Off
Mode	Frequency (Hz)	Frequency (Hz)	Frequency(Hz)
1	18.983	19.022	19.021
2	21.663	21.655	21.655
3	21.790	21.782	21.782
4	31.525	31.501	31.501
5	31.635	31.611	31.612
6	129.653	129.564	129.577

Note the frequency does not change during the beam cycling. This means the temperature has a very little effect.

Target First Mode Shape When Beam is on



Target Second Mode Shape When Beam is on



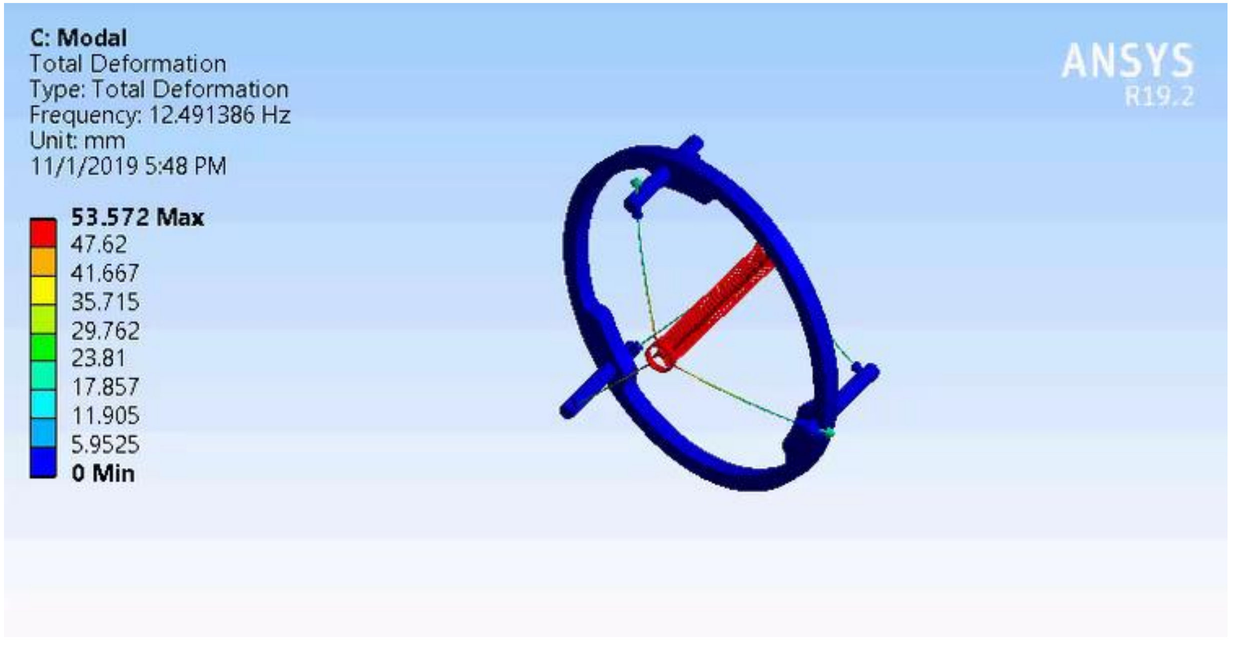
Target under NON Pre-stressed Condition

	Bicycle Ring and Posts Included
Mode	Frequency (Hz)
1	12.49
2	12.64
3	13.57
4	15.15
5	18.24
6	18.25

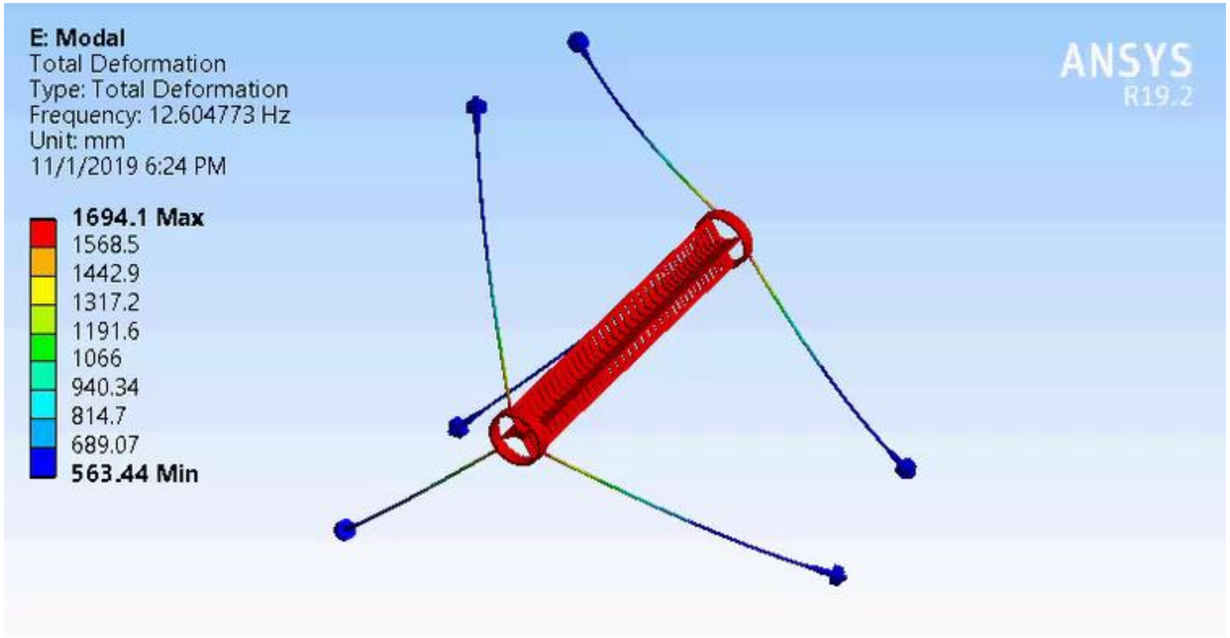
	Bicycle Ring and Posts Excluded
Mode	Frequency (Hz)
1	12.60
2	12.82
3	18.50
4	18.51
5	25.98
6	25.99

Note Bicycle Ring and Posts change the frequency only slightly

Target with Bicycle Ring and Posts First Mode Shape Under Non Pre-stressed Condition



Target without Bicycle Ring and Posts First Mode Shape Under Non Pre-stressed Condition



Part 5- Comments

The Target shall be shielded in the frequency range from 12 to 32 Hz due to possible resonance.

Conclusion

- **Hayman2 Target meets the design requirement.**
- **The maximum stresses at the concentration regions are expected due to the sharp corners and the slivers. These stress raisers can be modified by removal of the sharp corners at the slots and increasing the radii of the fillets.**
- **There is a stress excursion during the beam cycle. Fatigue may be a concern.**
- **Spoke and Target will not buckle due to the safety margin.**
- **Target shall be kept away from anything with the frequency range from 12 to 32 Hz to avoid resonance.**
- **Cold Work option should be considered in order to increase the creep limit at higher temperature.**